Feedback-Dependent Threshold of Electrically Pumped VECSELs

Wolfgang Schwarz

We present the investigation of the feedback-dependent threshold of an 822 nm wavelength electrically pumped vertical-external-cavity surface-emitting laser (VECSEL). The setup is capable of resolving micrometer-size features on the laser surface, while demanding highly accurate alignment. Modified design criteria are developed, which address this issue, and approaches for the fabrication of miniaturzied devices are outlined.

1. Introduction

In biochemical analysis, the trend to smaller systems has progressed to the detection of volumes in the sub-femtoliter range [1,2]. Such small volumes allow the observation of single molecules together with an economic utilization of the investigated substances. Unlike an integrated sensing scheme, which makes use of single-pass excitation [3], the detection limit can be improved when the detected particle is located inside an optical resonator. The advantages of using vertical-cavity surface-emitting lasers (VCSELs) in such an arrangement are electrical pumping with low operating currents, the potential for low cost, and the circular output beam with the ease of building a stable resonator. The latter has been demonstrated in electrically and optically pumped devices with high efficiencies [4] and even for intra-cavity frequency doubling [5], where a strong field enhancement is required. In intra-cavity sensing, this enhancement is desired as well.

A stable two-mirror resonator incorporating a plane mirror, namely the VCSEL aperture, and an external curved mirror with the radius of curvature ρ supports a laser beam with a spot size w_0, where $w_0^2 = M^2\lambda\sqrt{L\,(\rho - L)}/\pi$ with λ as the wavelength, L as the resonator length, and M^2 as the beam propagation factor [6,7]. The beam waist is located on the plane mirror. The beam propagation factor describes the diffraction angle of the actual beam in comparison to a Gaussian beam with $M^2 = 1$. Real beams show $M^2 \geq 1$, which reflects the fact that for a given spot size, propagating Gaussian beams broaden the least. The beam spot size is plotted in Fig. 1 versus the resonator length for different beam propagation factors and radii of curvature of 10.3 mm and 250 µm. It is apparent from the diagrams that the beam size scales with the radius of curvature and amounts to about 30 µm for the long resonator and 5 µm for the short resonator. Hence a small beam waist is only attainable with a small radius of curvature. In Fig. 2, the length of stable resonators is depicted for both configurations. If the resonator length approaches the radius of curvature of the external mirror, the beam propagation factor becomes infinitely large, which means high diffraction and higher aperture losses. Stable operation of the long resonator with a spot size of 5 µm can only occur if its length differs by not more than a fraction of a micrometer from the maximum stable length. This requirement is much relaxed in the short resonator. Here the same spot size is attainable by varying the resonator length within 40 µm. These calculations show that the longitudinal alignment of the longer cavity is extremely critical and that for a hybrid fabrication approach, a shorter resonator is favorable.

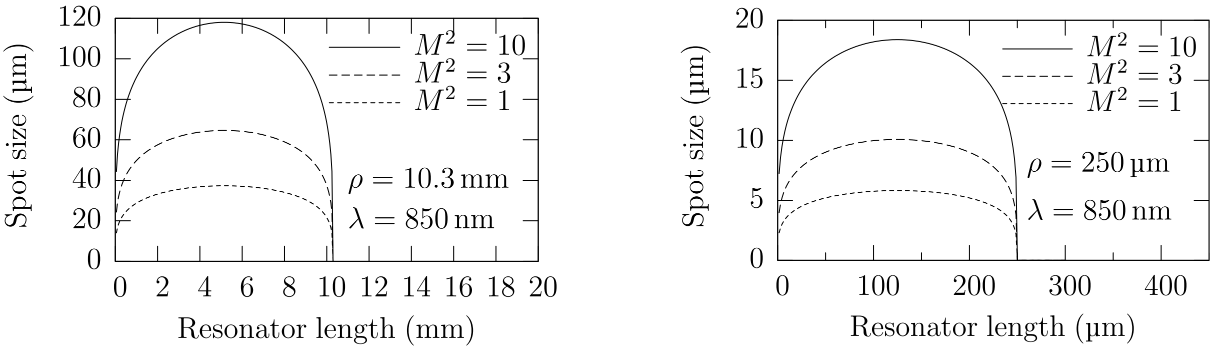

Fig. 1: Calculated beam spot size at the plane mirror versus the length of a plano-convex resonator with radii of curvature of 10.3 mm (left) and 250 µm (right) and different beam propagation factors.

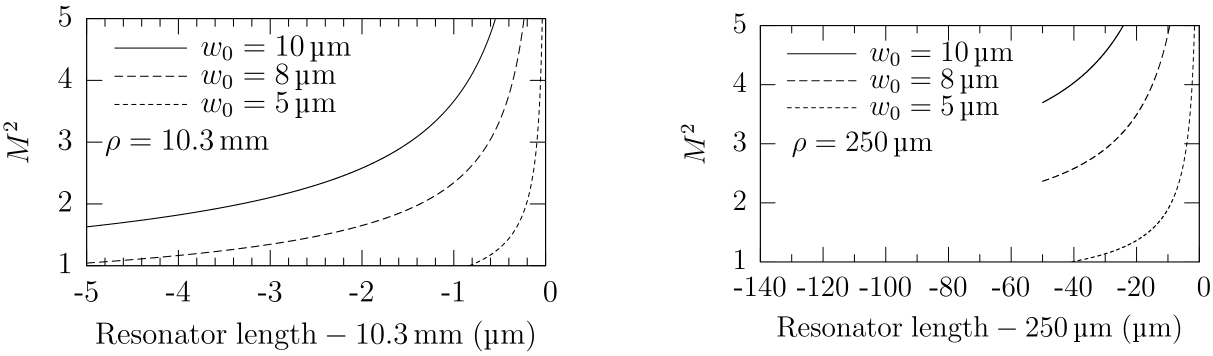

Fig. 2: Calculated beam propagation factor M^2 for different resonator lengths and beam spot sizes. Curved mirrors with $\rho = 10.3$ mm (left) and 250 µm (right) are assumed. The wavelength is 850 nm.

2. Setup and Device Fabrication

The properties of lasers may change significantly when optical feedback is introduced. A shift of the threshold current as well as a modified mode pattern and polarization are typically observed, the latter two particularly in VCSELs [8]. The present investigation is limited to the threshold behavior. A laser is a resonant device, whose resonance condition is dependent on the phase and amplitude of the back-reflected field. In the investigated regime, the external roundtrip delay time is of the same order (in the present case of $L = 10.3$ mm about 68 ps) as the inverse of the relaxation oscillation frequency of the laser. Here, small changes of the resonator length result in an alteration of the phase condition and of the laser threshold.

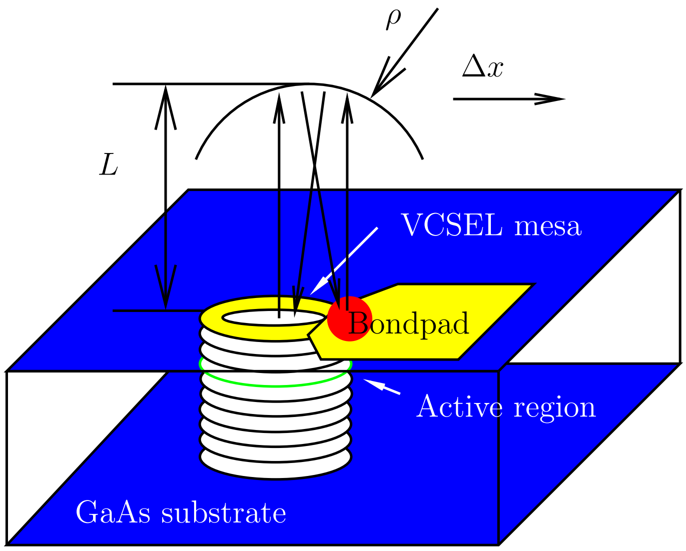

Fig. 3: Schematic drawing of the experimental setup used for the feedback investigations and simplified ray paths for a lateral displacement of the external mirror by an amount Δx.

Figure 3 shows a schematic of the setup. The system comprises a top-emitting VCSEL grown by molecular beam epitaxy. The 822 nm emission wavelength was detuned from the gain peak in the applied GaAs/AlGaAs material system. The active zone of the laser consists of three 8 nm thick quantum wells embedded in 10 nm thick barriers. The active diameter was defined by wet etching of the mesa and subsequent selective oxidation to a diameter of 10 µm. The resonator mirrors consist of 38 n-doped and 23 p-doped distributed Bragg reflector (DBR) pairs. The external mirror made of BK7 glass was coated by plasma-enhanced chemical vapor deposition (PECVD) at 300°C with 8 pairs of Si_3N_4/SiO_2 in order to achieve a reflectivity of 80 % at the operation wavelength. To assess the surface quality, the coating was also applied on a silicon wafer piece. Atomic force microscopy measurements revealed a surface roughness R_s of 4.3 nm root mean square (RMS) resulting from this procedure in comparison with uncoated silicon with $R_s = 0.2$ nm.

At a rough surface with a Gaussian height distribution, the calculated ratio between total scattered and incident light is approximately $1 - \exp\{-(\pi R_s/\lambda)^2\}$ [9]. In the present case, the ratio amounts to $2.5 \cdot 10^{-4}$ and appears negligible when compared with the mirror transmittivity of about 20 %.

The external mirror was mounted on a three-axes positioning system, which was operated unidirectionally for minimum backlash. The plano-concave coated side with a radius of curvature of 10.3 mm faced the VCSEL aperture. During the experiment, the laser was electrically contacted with a needle, which was placed on the bondpad next to the VCSEL mesa.

3. Experimental Results

The threshold of a real laser resonator depends on several parameters such as material absorption, aperture losses, surface scattering, alignment tilt, as well as lateral and longitudinal confinement factors. This contribution investigates the feedback-dependent threshold of a VCSEL.

The light–current (LI) characteristics at power levels close to the VCSEL threshold was recorded (Fig. 4). It was difficult to align the external mirror in a manner that a shift of the threshold current could be observed. The distance between VCSEL mesa and external mirror was slightly smaller than the radius of curvature of the external mirror and had to be kept within a range of less than one micrometer in order to maintain the conditions for low threshold. For mapping the spatial dependence of the feedback on the threshold, the external mirror was displaced laterally and the LI characteristics were recorded in the vicinity of the threshold. The threshold currents were determined by linear regression and are depicted in Fig. 5. The spatially resolved laser threshold clearly represents losses in the resonator. As sketched in Fig. 3, the resonator mode experiences scattering at the etched mesa when the mirror is displaced radially by about half a mesa radius. The actual mode will not shift laterally by twice the displacement, but rather find a position with lower losses. A model as proposed in [10] could predict this loss mechanism more in detail. The setup is even capable of resolving the footprint of the bondpad, where scattering also occurs. The shift in laser threshold ranges from 2.65 mA without feedback to 2.4 mA with feedback. A transfer matrix model predicts a shift in threshold gain from about $4500\,\mathrm{cm}^{-1}$ to $2600\,\mathrm{cm}^{-1}$ and a related shift in threshold current from 2.1 to 0.5 mA for the given structure and reflectivities, assuming a current–gain dependence from [11] and an internal absorption in the DBR mirrors of $100\,\mathrm{cm}^{-1}$, where gain detuning as well as internal heating are not considered.

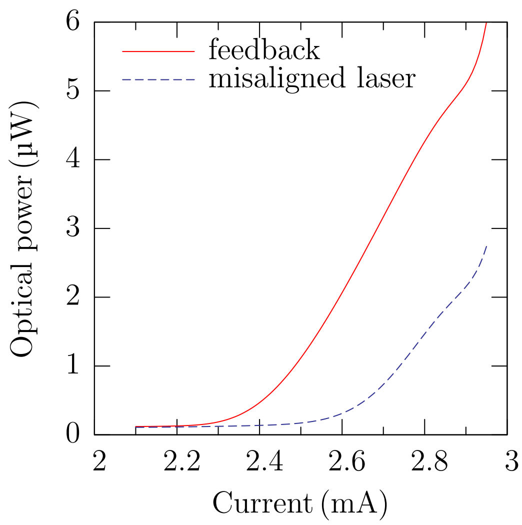

Fig. 4: LI characteristics of the investigated VCSEL with and without optical feedback. Feedback was suppressed by intentionally misaligning the resonator. The optical power was measured through the external mirror, such that just a fraction of the total power was detected.

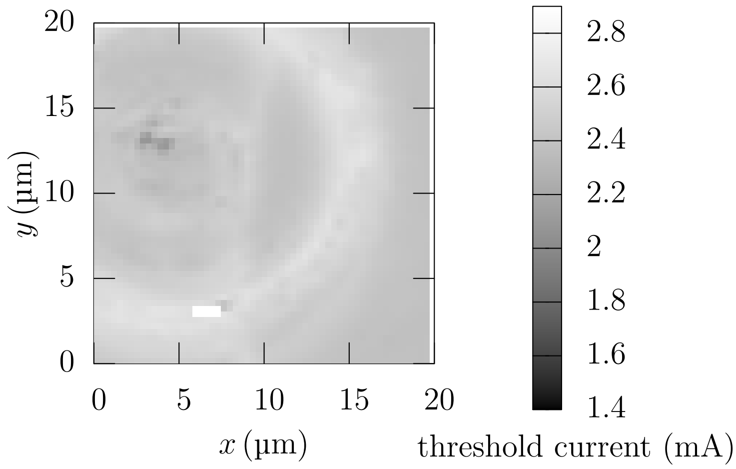

Fig. 5: Two-dimensional map of the VCSEL threshold current at different lateral displacements of the external mirror.

4. Conclusion

A setup for the determination of the feedback-dependent threshold of a vertical-cavity surface-emitting laser facing a curved external mirror is introduced. The setup is very sensitive to misalignment, in accordance with a prediction from a wave-optical model. A 80 % reflective external mirror produced about 10 % relative change in threshold current, which somewhat deviates from the change predicted by a simplified gain model. The relatively low modulation of the threshold current may be attributed to an unidentified loss mechanism. Possible candidates could be an unexpectedly high scattering loss in the external mirror, fundamental absorption in the topmost GaAs layer in the VCSEL aperture, or the critical alignment with possible scattering loss from higher-order mode excitation.

Devices with a shorter cavity are to be considered for a hybrid-integration approach. These devices are less prone to longitudinal resonator length misalignment. Preferably, the lateral alignment of such devices has to be provided by self-alignment features. In this case, the alignment can be achieved with photolithographic precision, which is a prerequisite for low resonator losses.

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